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Laboratory Particle Velocity Experiments on Rock From a USSR Underground Nuclear Test Site

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333 Ravenswood Avenue
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This technical report has been reviewed and is approved for publication.

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Particle velocity histories were measured in spherical wave experiments performed in Sierra White granite (1) to test a technique for increasing the useful signal duration for experiments in small diameter cores obtained from the joint verification experiment (JVE) site, and (2) to determine the effects of the pore space condition on the wave propagation and attenuation.

The technique used to increase the useful signal duration involved inserting a 6-cm diameter core into a borehole drilled in a 16-cm diameter specimen of the same material. The records from experiments with and without the core/borehole interface showed no effect of this interface. This technique can be used on the 6-cm diameter JVE cores.

Three experiments were performed to compare different initial pore conditions: (1) dry, (2) saturated with equal overburden and pore pressures, and (3) saturated with 11.7 MPa effective stress. The results showed that any effects of initial pore condition are within experimental scatter. Therefore, an initial effective stress is not needed for future experiments, and they will be performed saturated with equal overburden and pore pressures.

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program to be completed in the next year of this contract, during which we will perform experiments on rocks from the JVE site and in samples obtained from a potential analog site in Maine.

PREFACE

This research was conducted under Contract F-19628-88-K-0051. Dr. James Lewkowicz was the technical monitor.

The authors are indebted to the following personnel at SRI International for their contributions to this research: E. M. Oyola for preparing and performing the experiments, M. A. Merritt for electronic instrumentation, and D. E. Hutson for machining the specimens.

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SECTION 1

INTRODUCTION

The objective of this research project is to support the DARPA program for calibrating the Soviet nuclear test site by generating spherical waves in granite obtained from a borehole drilled adjacent to the site of the joint verification experiment (JVE). At first, our experimental effort focused on the JVE rock; however, this has been modified to include experiments to determine the effects of pore fluid and nonzero effective stress on attenuation and experiments on a suite of rocks obtained from Maine as a possible analog to the JVE rock. We also performed some experiments in technique development to accommodate the small-diameter (6-cm) JVE cores and to extend the duration of measurements before boundary reflections arrive at the measurement positions.

Specifically, our objectives are (1) to determine the effects of pore fluid and effective stress on velocity and displacement attenuation, (2) to generate radial particle velocity histories at different radii from a spherical explosive source in both the JVE rock and rock specimens from Maine and compare the results, (3) to generate strain histories and strain path data from the spherically divergent dynamic loading condition, and (4) to determine if attenuation in hard (low-porosity) rock is independent of the rock constituents (i.e., compare different types of granite, metamorphosed limestone, etc.).

In this report, we present the results of the technique development effort to extend the useful signal duration and the effects of pore fluid and effective stress on wave propagation. Because of the limited number of Maine and JVE specimens, we used Sierra White granite for the technique development and pore fluid effects experiments.

In Section 2, we present the setup for the experiments; the results are in Section 3. During the next year of this contract, we will complete the experiments listed in the test matrix shown in Table 1.

Table 1. TEST MATRIX FOR JVE/ANALOG ROCK

Rock Type	Load Condition	P_{eff} (psi)	Tests	Objective
Sierra White granite[a]	P_c = 2000 psi P_p = 0	Dry	1	Determine the effect of pore fluid and effective stress on coupling/attenuation of intact hard (low-porosity) rock
	P_c = 2000 psi P_p = 2000 psi	0	1	
	P_c = 2000 psi P_p = 0	2000	1	
JVE	P_c = 2000 psi P_p = 1000-2000 psi	0-1000	2	Measure velocity, displacement, and strain histories/attenuation in JVE rock under divergent loading
Analog (Maine)				
Limestone	P_c = 2000 psi P_p = 1000-2000 psi	0-1000	2	Compare response of three different rock types to determine (1) if coupling and attenuation are comparable to those of JVE rock and the rock is a suitable analog, and (2) if coupling in "hard rock" is independent of rock type
Coarse-grained granite	P_c = 2000 psi P_p = 1000-2000 psi	0-1000	2	
Fine-grained granite	P_c = 2000 psi P_p = 1000-2000 psi	0-1000	2	

[a]Completed.

SECTION 2

EXPERIMENTAL SETUP

2.1 TECHNIQUE DEVELOPMENT

The specimens obtained from the Soviet test site are available in 6- and 10-cm-diameter cores. For the particle velocity (PV) experiments, 10-cm cores would provide signal durations up to approximately 20 µs before reflections arrived from the specimen boundary, which time is probably suitable for the purposes of the experiment. However, the number of competent 10-cm cores is limited, so 6-cm cores may need to be included in the testing program. For 6-cm cores, the signal duration before the arrival of boundary reflections is insufficient. We therefore developed and tested a technique to extend the useful signal duration by inserting a 6-cm core into a borehole of a larger diameter specimen of similar shock impedance. The objective was to ensure intimate contact between the core and borehole, thereby minimizing (or eliminating) reflections from this interface. We tested interface reflection effects by comparing particle velocity histories in two experiments on dry Sierra White granite; one included a core/borehole interface, and one was performed without an interface.

The experimental configuration is shown in Figure 1. In these experiments, a 3/8-g spherical charge of PETN powder, packed to a density of 1 g/cm^3, is detonated at the center of a granite specimen. Concentric copper loops are placed in machined grooves at radii of 1.0, 1.5, 2.0, and 4.0 cm from the center of the charge. Particle velocity is measured by monitoring the induced voltage of the copper loops as they move at the local particle velocity through an externally applied magnetic field. Particle velocity is proportional to the conductor length, the induced voltage, and the magnetic field strength. A hydrostatic overburden pressure of 14 MPa is applied to each specimen.

We prepared the specimens by grinding their faces flat and machining a spherical cavity for the charge and grooves for the particle velocity loops. For the interface effects experiment, the circumference of the 6-cm-diameter core was ground and hand-lapped to produce a close fit into a machined borehole of the surrounding granite. Both the core and borehole were cut at a narrow angle (~1 degree), allowing for intimate contact with a press fit of the core into the borehole.

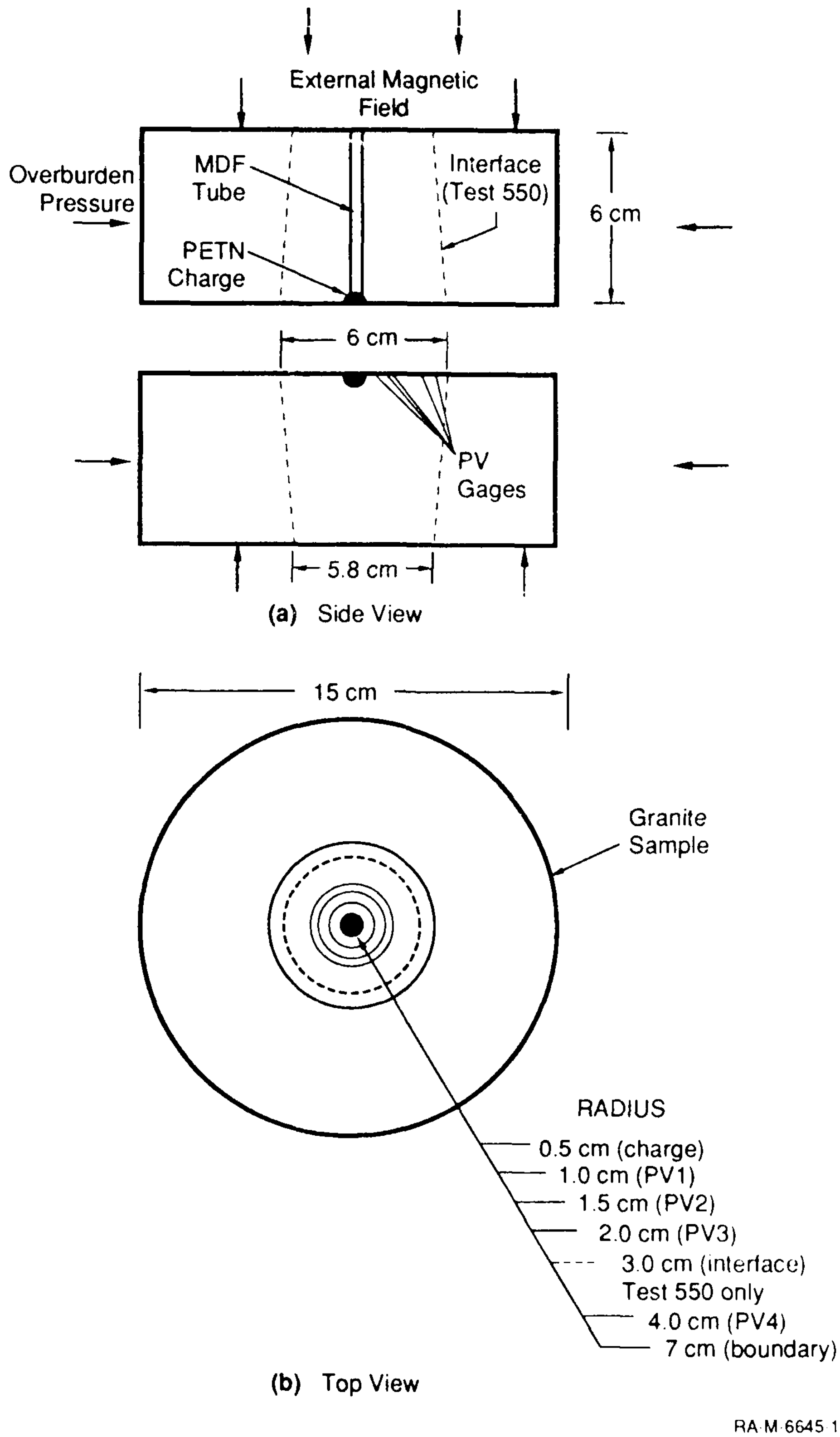

Figure 1. Configuration of particle velocity experiments in Sierra White granite to extend useful recording duration of small cores.

Test 550 (with interface), Test 551 (without interface).
(a) Side View
(b) Top View

2.2 EXPERIMENTS ON THE EFFECTS OF PORE FLUID

We performed three experiments in Sierra White granite with porosity <1% to compare the response for different pore conditions: (1) dry, (2) saturated with equal overburden and pore pressures of 11.7 MPa, and (3) saturated with 11.7 MPa initial effective stress. The experimental configuration for the dry and saturated case with zero effective stress is shown in Figure 2. In the experiment with nonzero initial effective stress, the pore pressure was isolated from the overburden pressure by surrounding the saturated specimen with a fine wire mesh that acted as a reservoir for the pore fluid. The sample and mesh were then surrounded by an aluminum sleeve around the circumference and end caps on the top and bottom with feed-throughs for water egress. Finally, this assembly was inserted in a rubber jacket and epoxied to the end caps. In these experiments, a 3/8-g charge of PETN powder was detonated at the center of a 16.5-cm-diameter cylinder of granite prepared for testing as previously described. Particle velocity histories were measured at eight radii from the center of the charge using the technique described in Section 2.1.

The specimens were saturated by (1) applying and maintaining a vacuum for 12-24 hours, (2) immersing the specimen in deionized/degassed water, and (3) applying an overburden pressure to the sample with a flatjack while maintaining a vacuum on the flat base of the cylindrical specimen for another 12-24 hours.

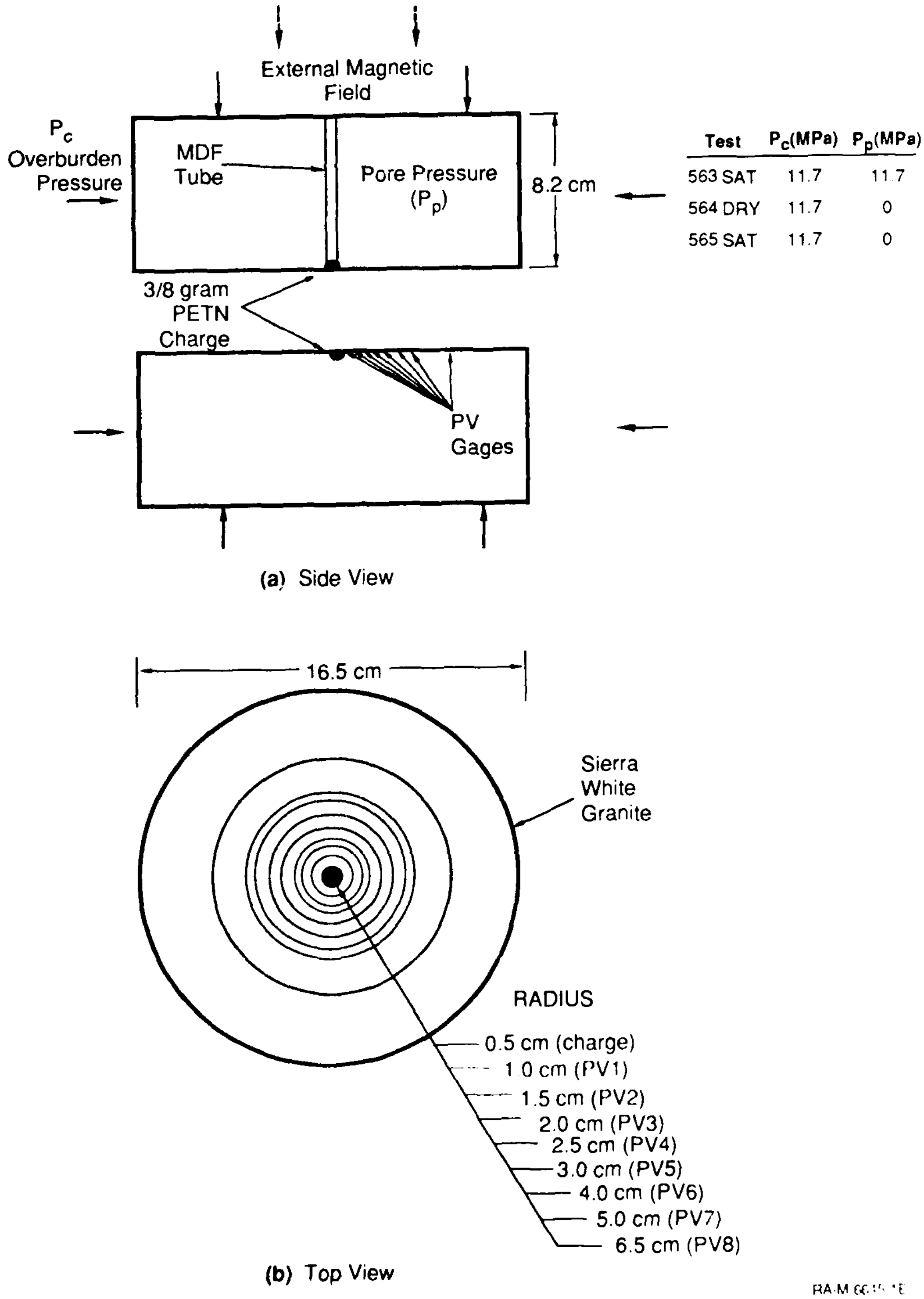

Figure 2. Configuration of particle velocity experiments in Sierra White granite to determine effects of pore condition on wave propagation.

SECTION 3

EXPERIMENTAL RESULTS

We uncovered a systematic 22% error in the determination of the magnitude of the magnetic field used in the data reduction procedure for obtaining particle velocity histories. Therefore, the particle velocity and displacement histories in the previously reported data on granite are 22% lower than the actual values. Because the error is constant in all measurements, only the magnitude of the values changes and therefore the overall pulse shape, attenuation rates, and conclusions drawn from the results are not affected. We have corrected the error and applied the compensating 1.22 scale factor to the pertinent data from past experiments in Sierra White granite.

3.1 TECHNIQUE DEVELOPMENT FOR EXTENDING RECORDING DURATION

Two experiments were performed to determine the effects of a core/borehole interface needed to extend the useful recording duration of small-diameter specimens. One experiment (Test 550) included an interface, and these results are compared with those from an experiment (Test 551) without an interface.

The results from Tests 550 and 551 are shown superimposed for each measurement location in Figures 3 through 6, and the displacements obtained by integration of the velocity records for both experiments are shown in Figure 7. In the particle velocity records, estimated arrival time from the core/borehole interface is indicated by "I" and reflections from the specimen boundary are denoted by "R." The gage records cannot be interpreted after reflections arrive from the specimen boundary. The reflection times for the two tests are different because of a 2-cm difference in specimen diameters.

As seen in Figures 3 through 6, the pulse shape, duration, and particle velocity amplitudes (except for the peak) are highly reproducible between the two experiments. In particular, we observed no effect of interface reflections in the experimental records because each feature seen in the specimen with an interface is reproduced in the specimen without an interface. The difference in peak particle velocity amplitude has little effect on the displacements as seen in Figure 7.

The secondary pulse in the particle velocity records at about 7 μs at the first location is probably the result of cavity reverberations. This pulse is propagated from the source

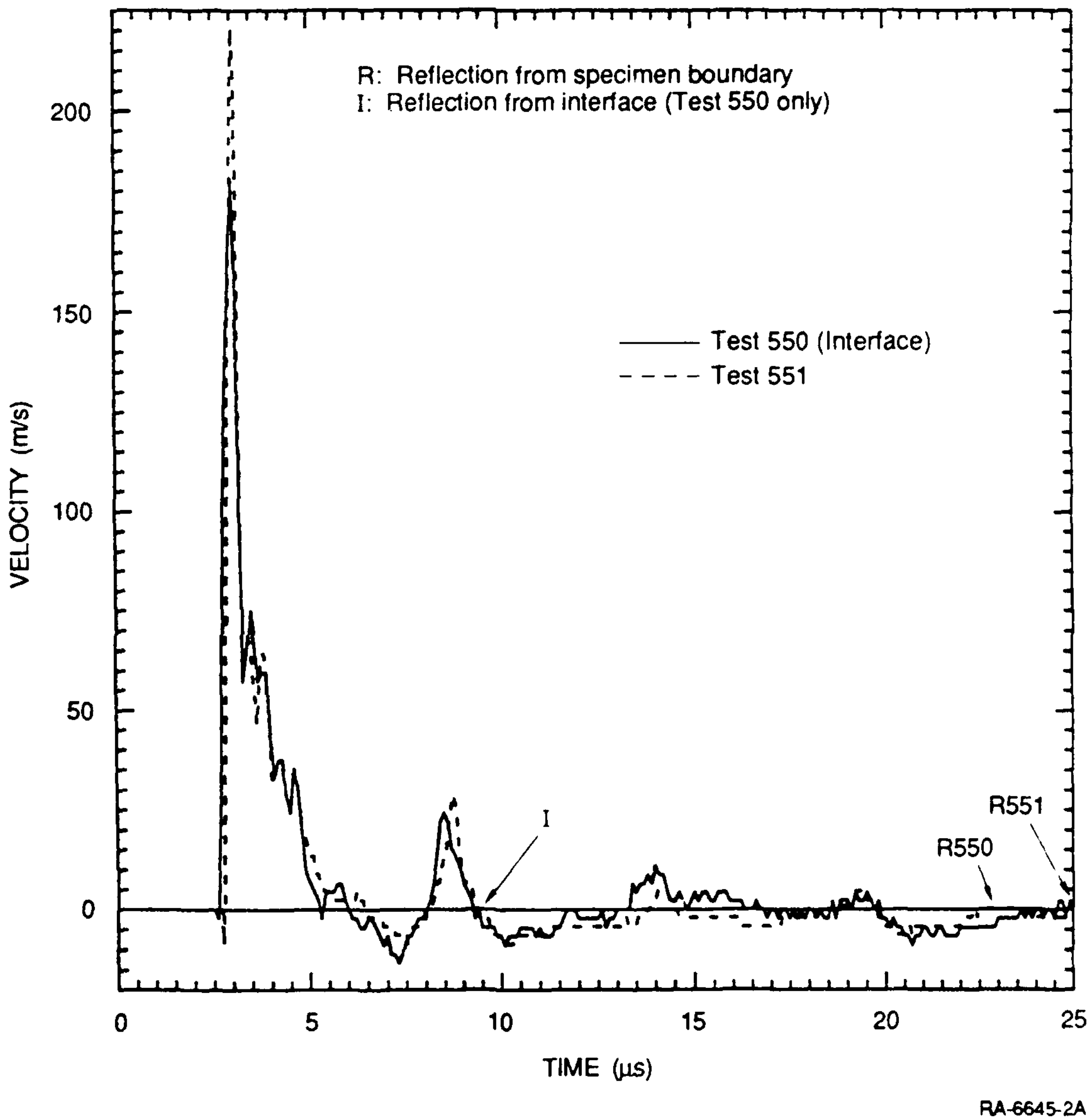

Figure 3. Radial particle velocity histories at a range of 10-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.

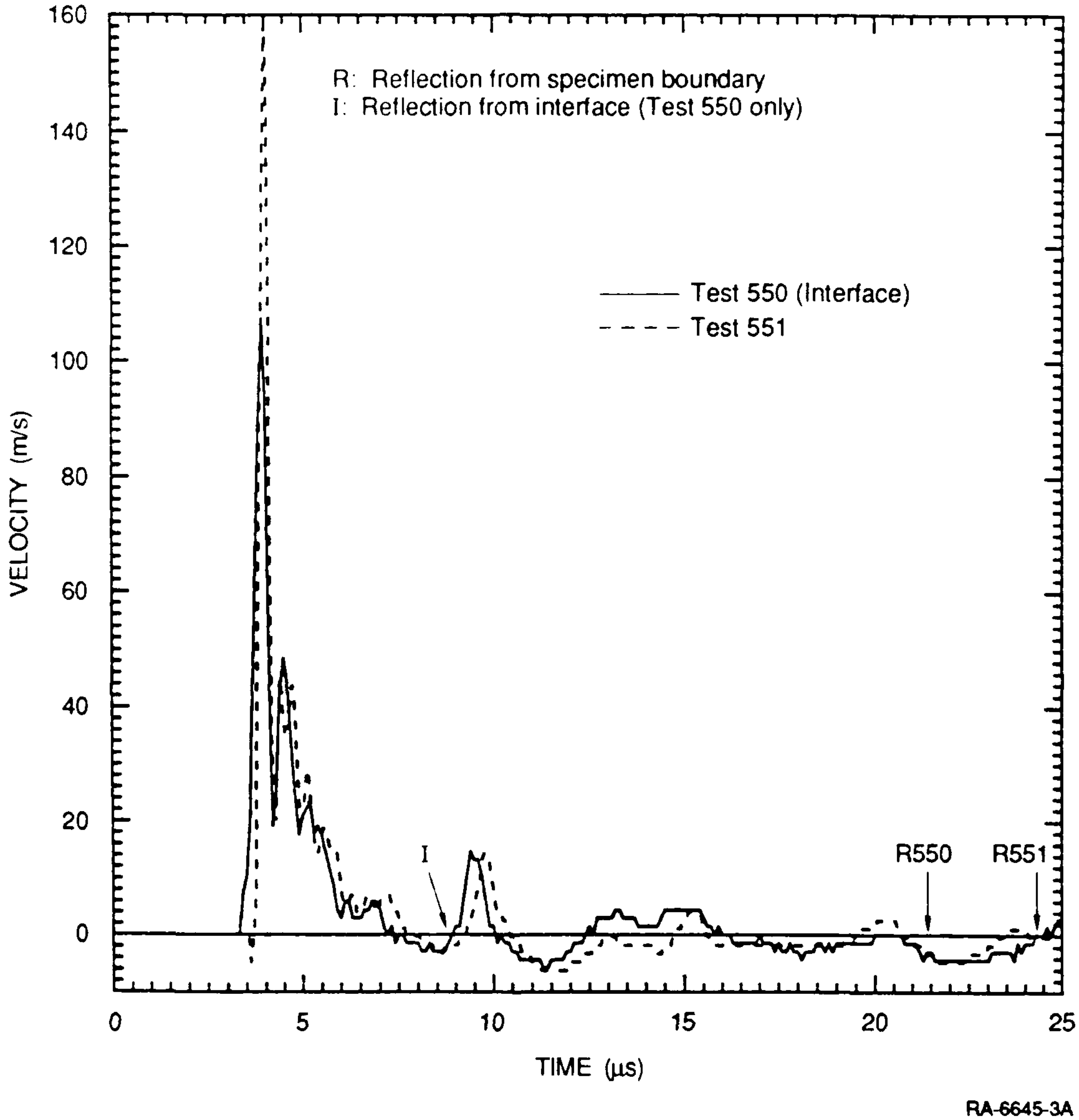

Figure 4. Radial particle velocity histories at a range of 15-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.

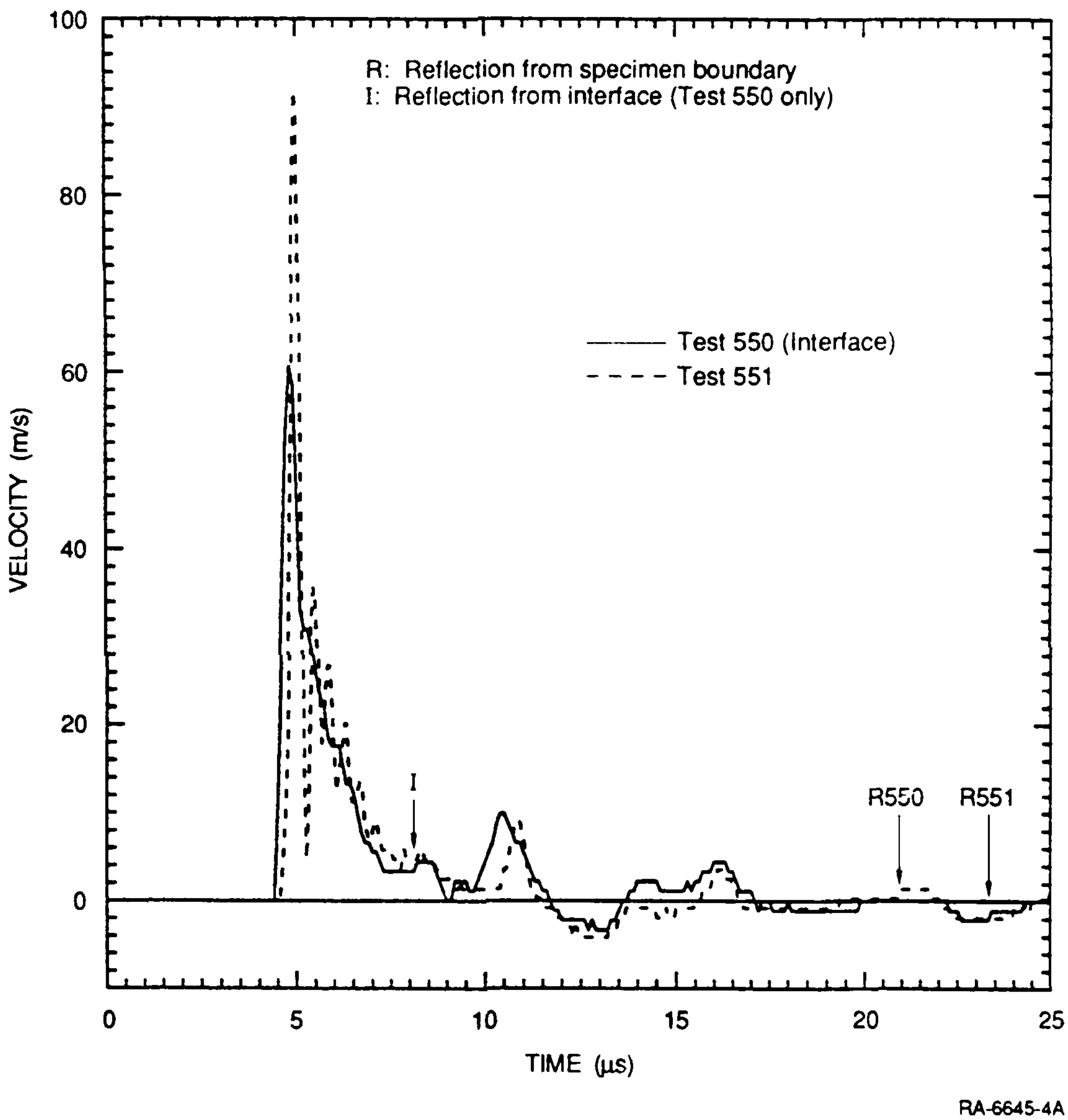

Figure 5. Radial particle velocity histories at a range of 20-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.

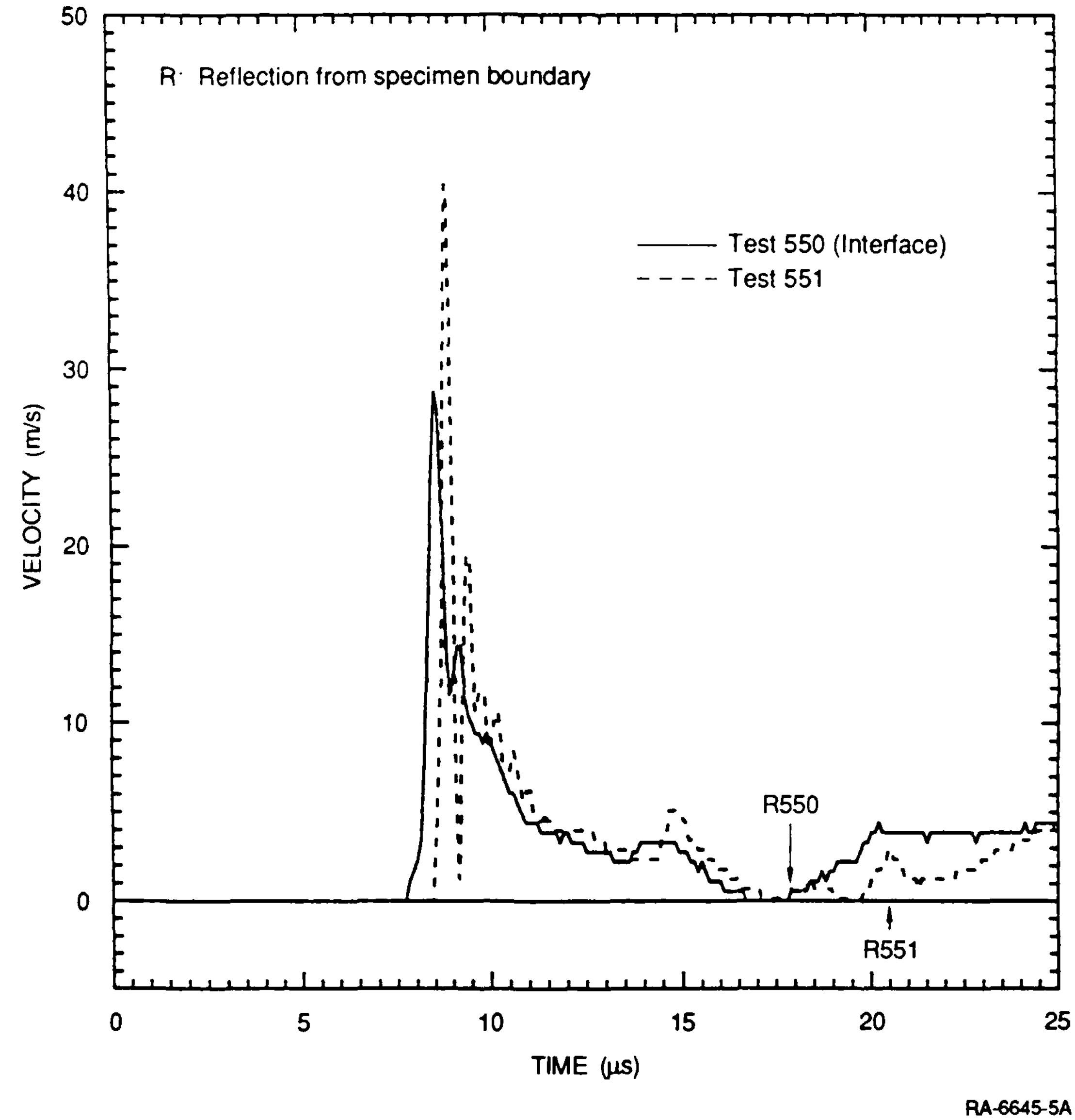

Figure 6. Radial particle velocity histories at a range of 40-mm in Sierra White granite comparing tests with (Test 550) and without (Test 551) an interface.

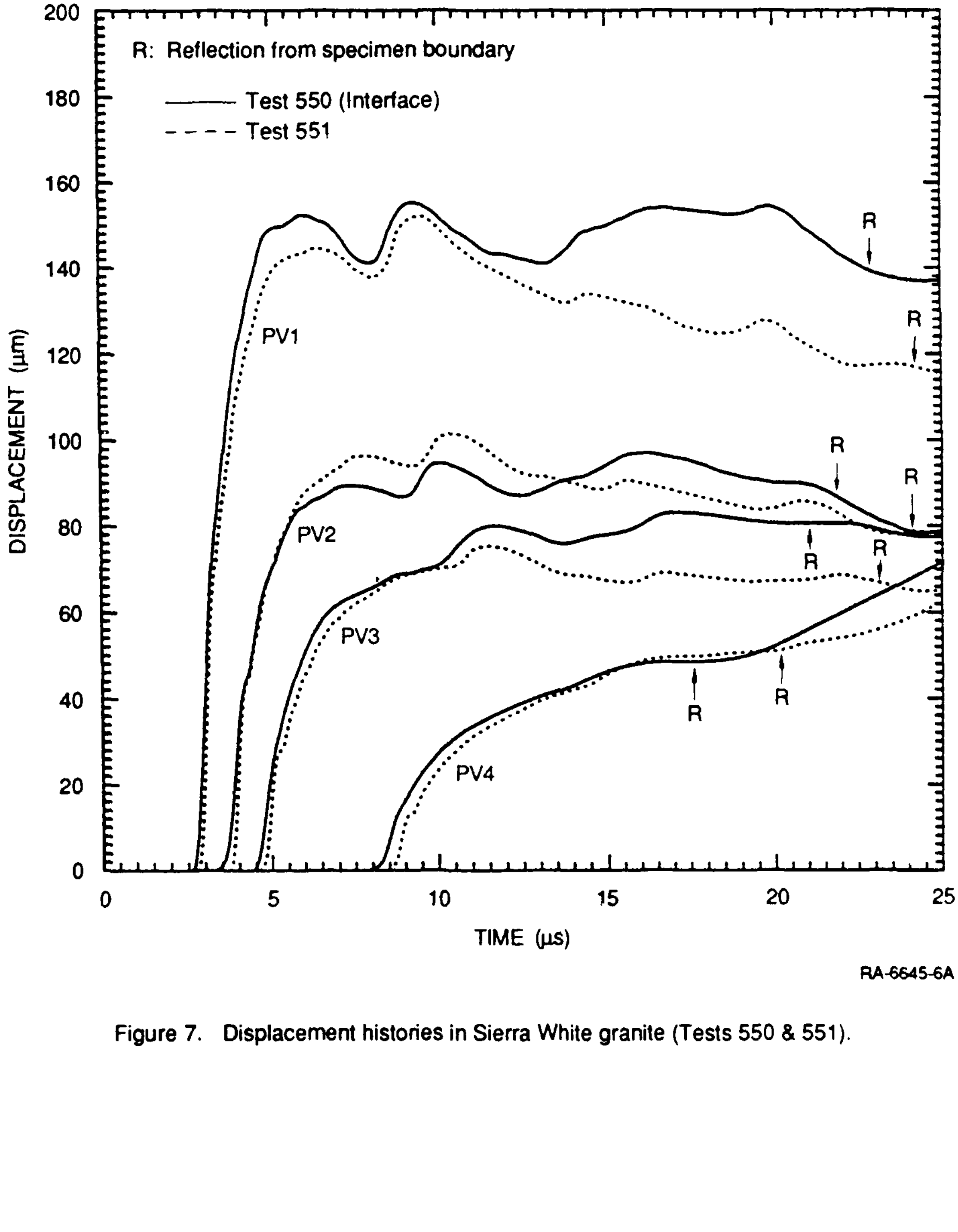

Figure 7. Displacement histories in Sierra White granite (Tests 550 & 551).

region because it arrives at each subsequent gage with reduced velocity at a later time. We believe the cause of the cavity reverberation is an initial cavity radius about 1 mm larger than the charge radius. In later experiments, the initial cavity radius was reduced to the charge radius to ensure intimate contact between the source and the medium.

3.2 PORE FLUID EFFECTS

The particle velocity records for the dry (Test 564), saturated with zero effective stress (Test 563), and saturated with 11.7 MPa effective stress (Test 565) experiments on Sierra White granite are shown superimposed at each gage location in Figures 8 through 15. The attenuation of peak particle velocity with scaled range is shown in Figure 16. The particle displacements, obtained by temporal integration of the velocity records, are shown superimposed at each gage location in Figures 17 through 24, and attenuation of peak displacement with range is shown in Figure 25. Unfortunately, we did not recover data from gages PV7 and in Test 563 because of a malfunction in the recording equipment. The peak velocity at the 3-cm and 4-cm locations in Test 565 also was not obtained because the oscilloscope used to record the data did not operate properly. Therefore, these data are not included in the velocity attenuation plots, but because they have little effect on the displacements, they are included in the displacement attenuation plots Cavity diameters were measured at about 1.3 cm.

The data from these experiments on low-porosity (<1%) Sierra White granite indicate that the effects of the pore space condition are negligible and cannot easily be resolved within the scatter of the experimental data. Therefore, the experiments on the JVE and analog rocks will be saturated with zero effective stress, which allows more experiments to be performed because of the less complicated sample preparation scheme.

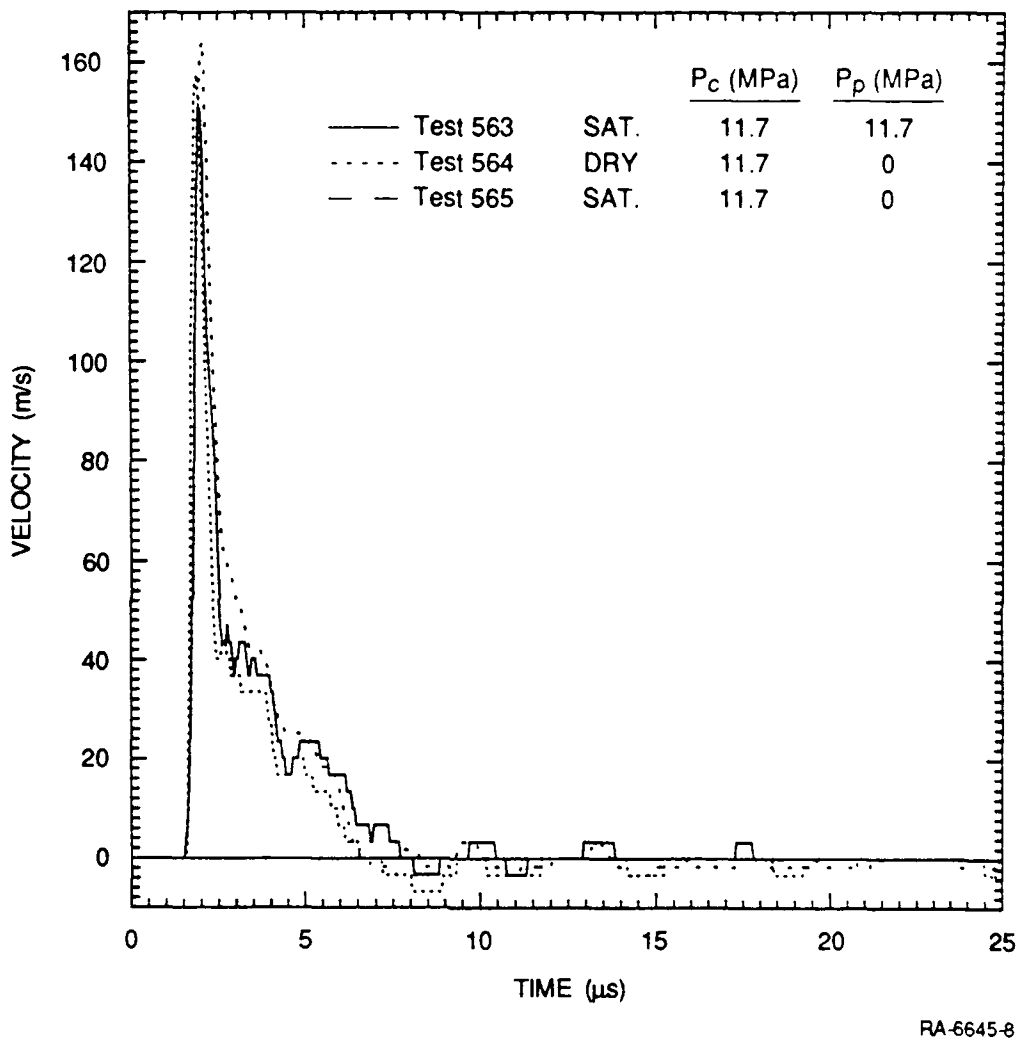

Figure 8. Particle velocity histories for three different pore conditions at 10-mm range in Sierra White granite.

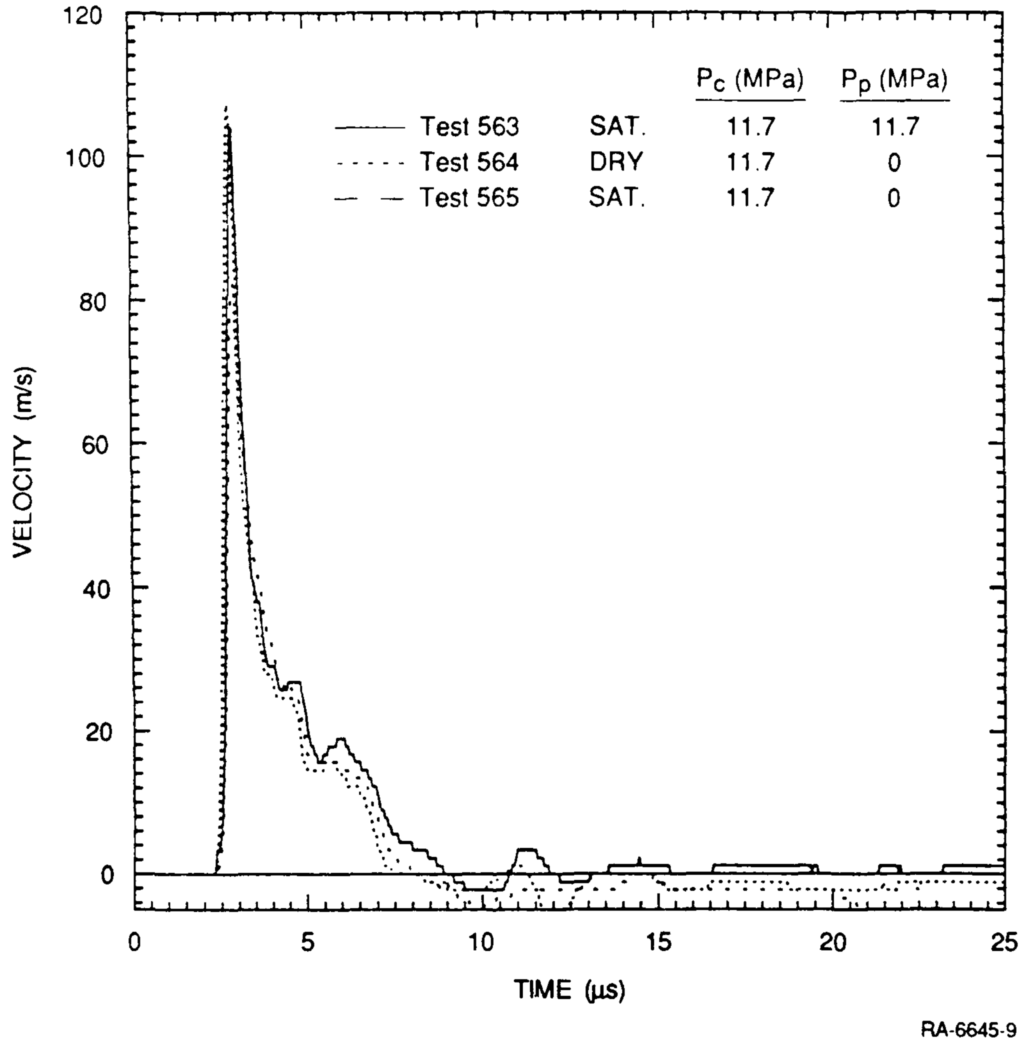

Figure 9. Particle velocity histories for three different pore conditions at 15-mm range in Sierra White granite.

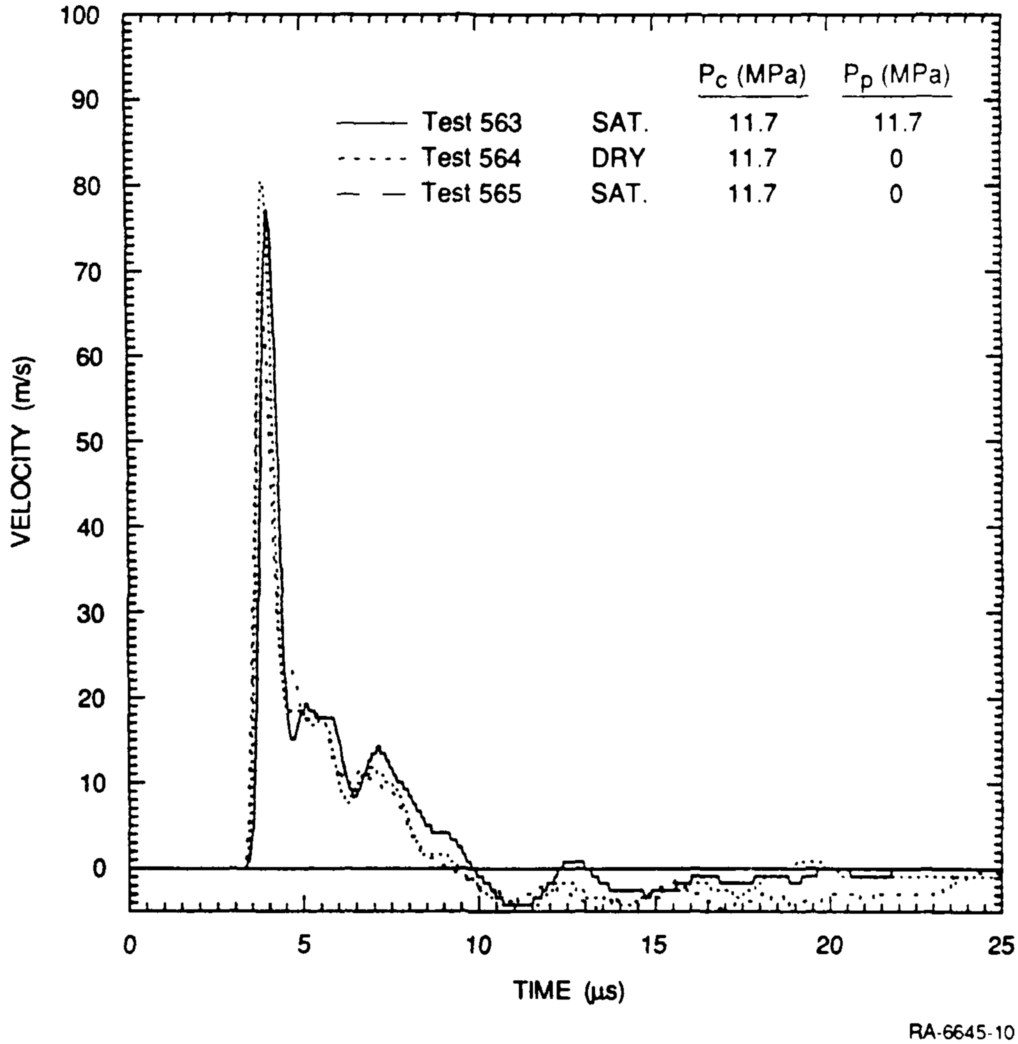

Figure 10. Particle velocity histories for three different pore conditions at 20-mm range in Sierra White granite.

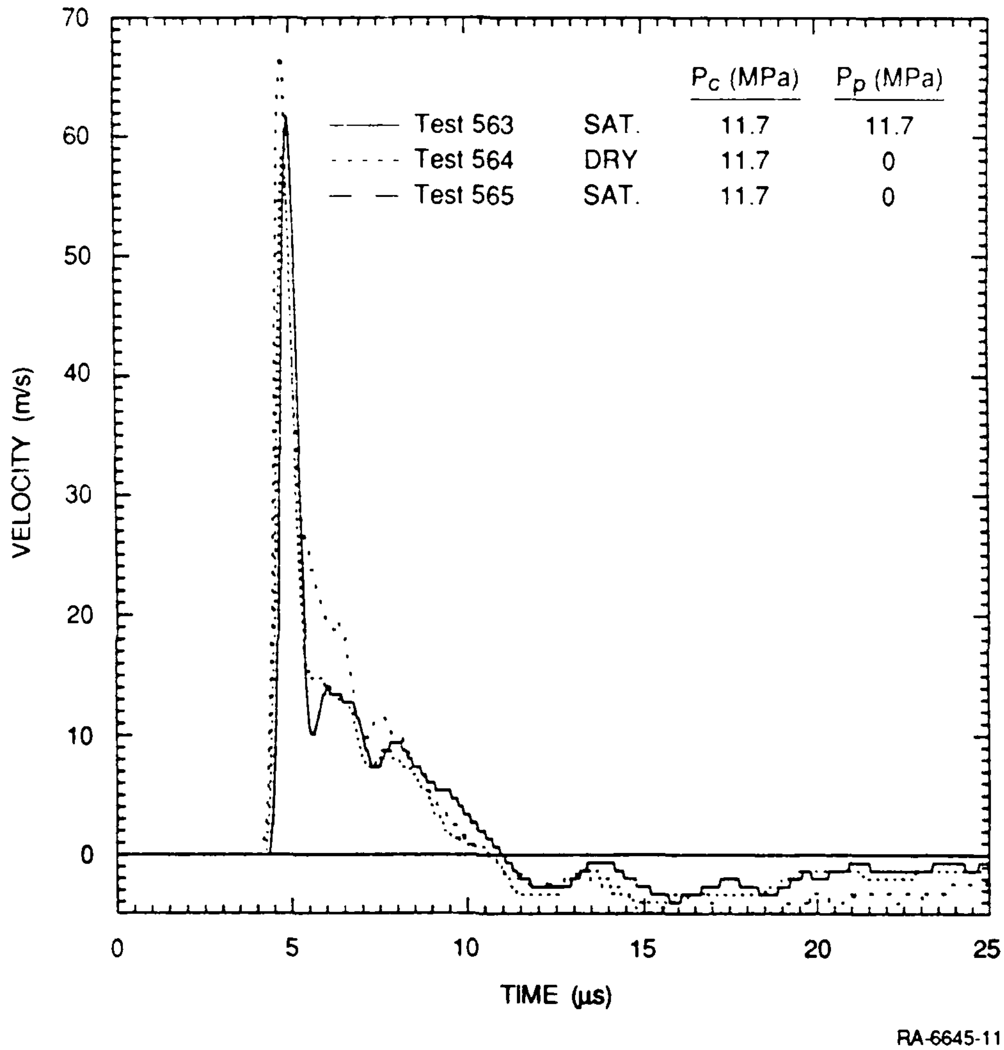

Figure 11. Particle velocity histories for three different pore conditions at 25-mm range in Sierra White granite.

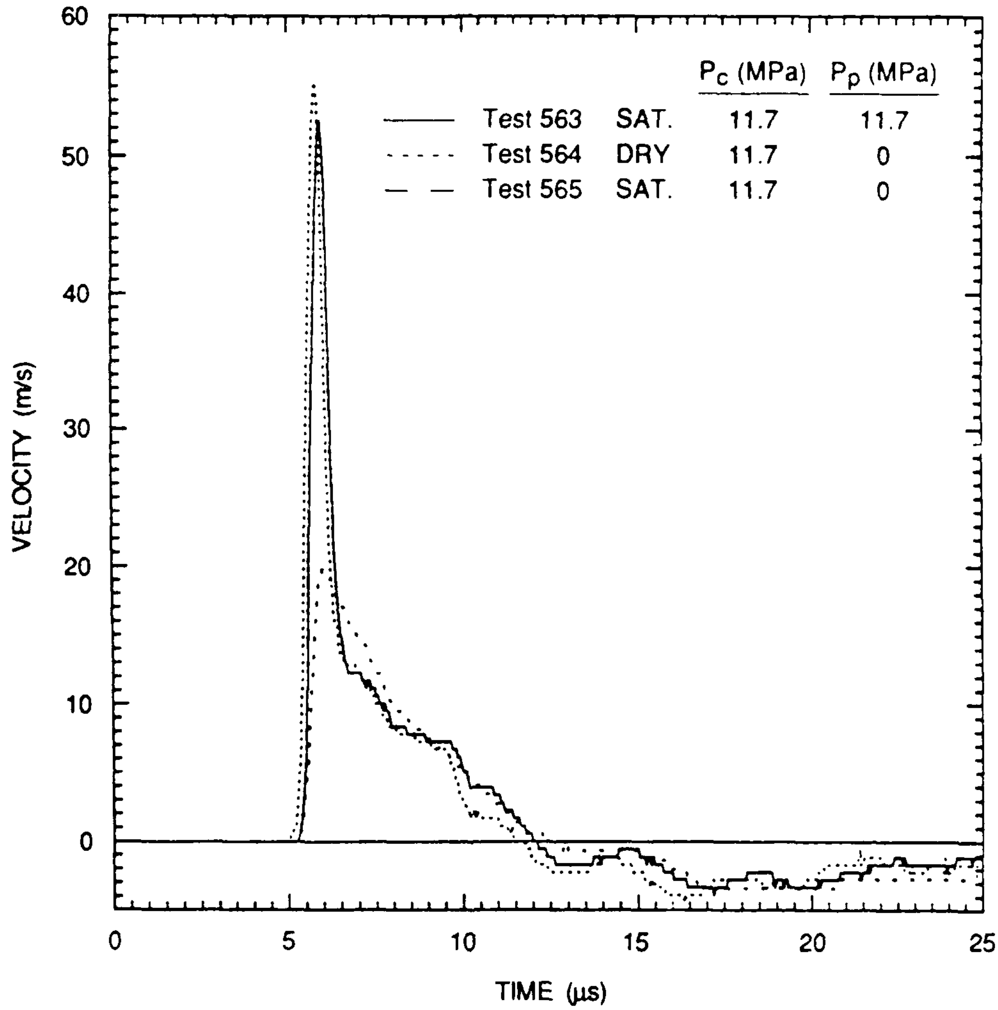

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Figure 12. Particle velocity histories for three different pore conditions at 30-mm range in Sierra White granite.

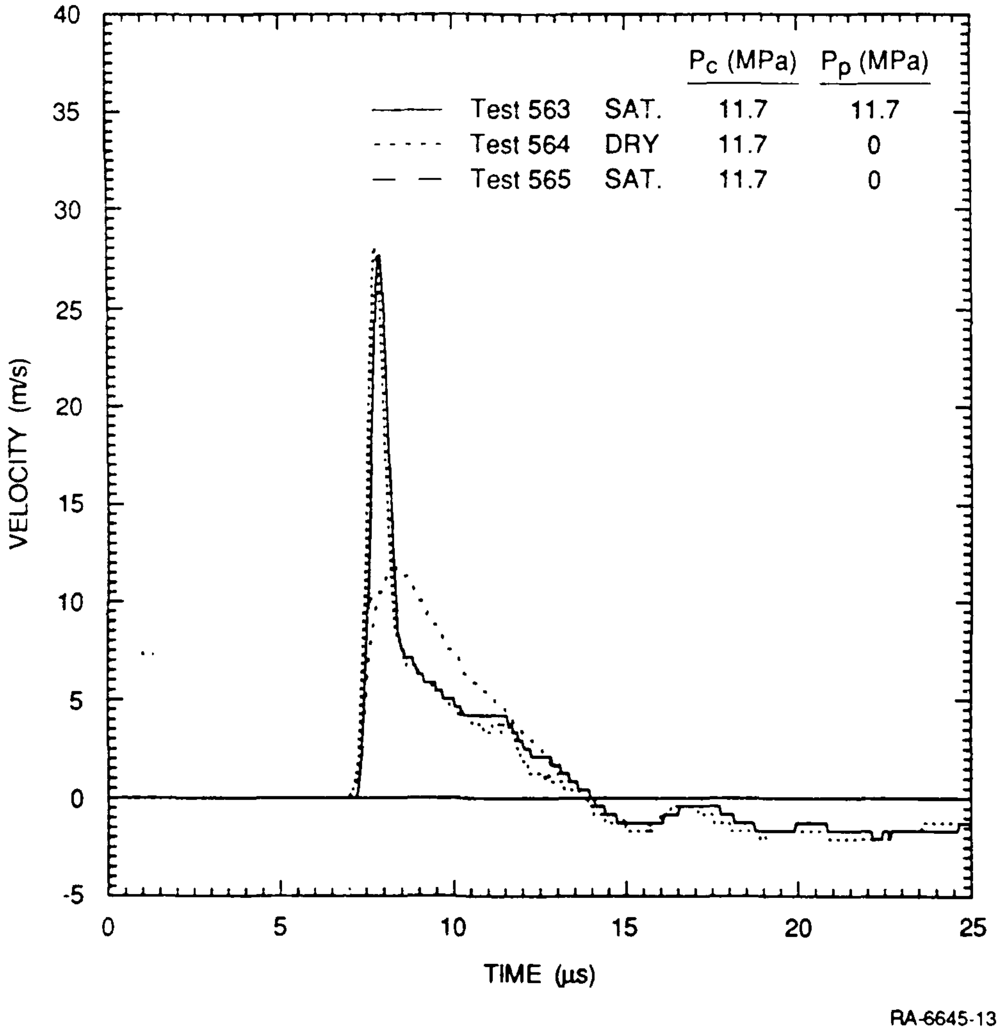

Figure 13. Particle velocity histories for three different pore conditions at 40-mm range in Sierra White granite.

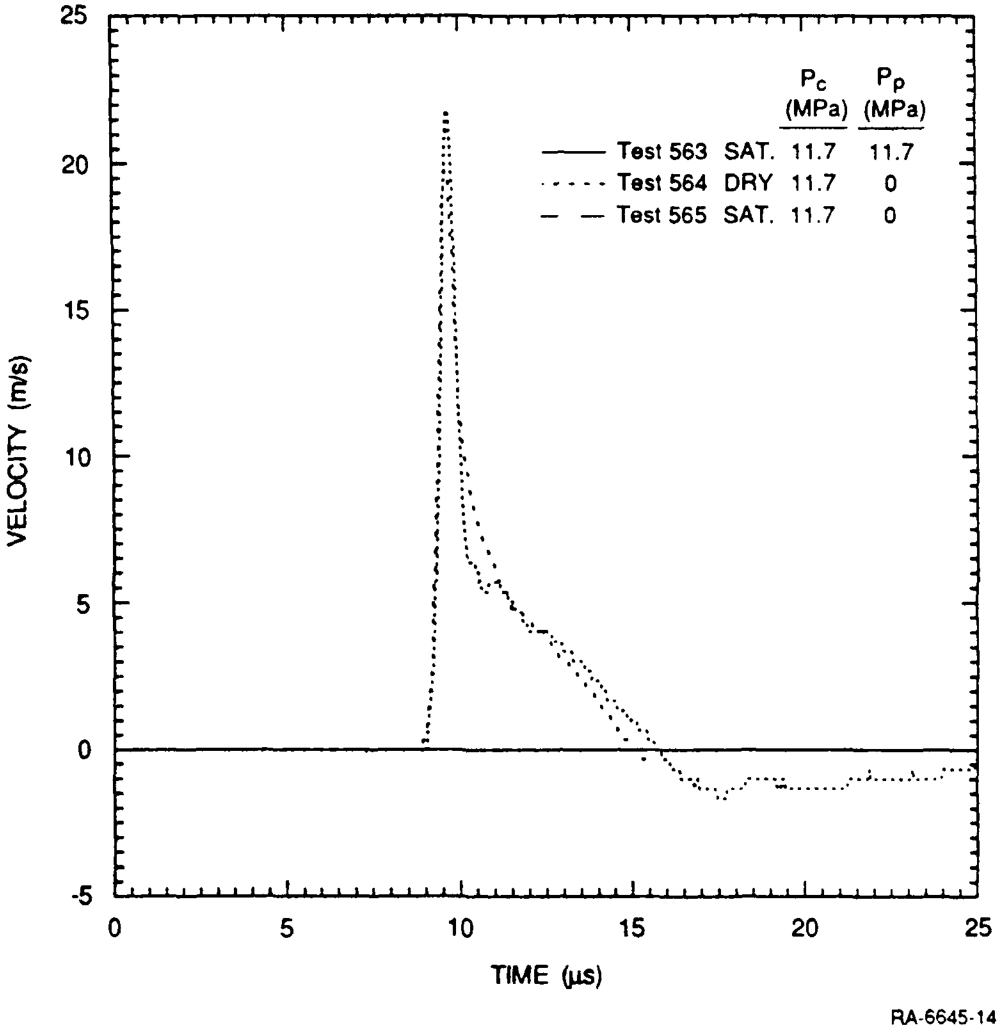

Figure 14. Particle velocity histories for three different pore conditions at 50-mm range in Sierra White granite.

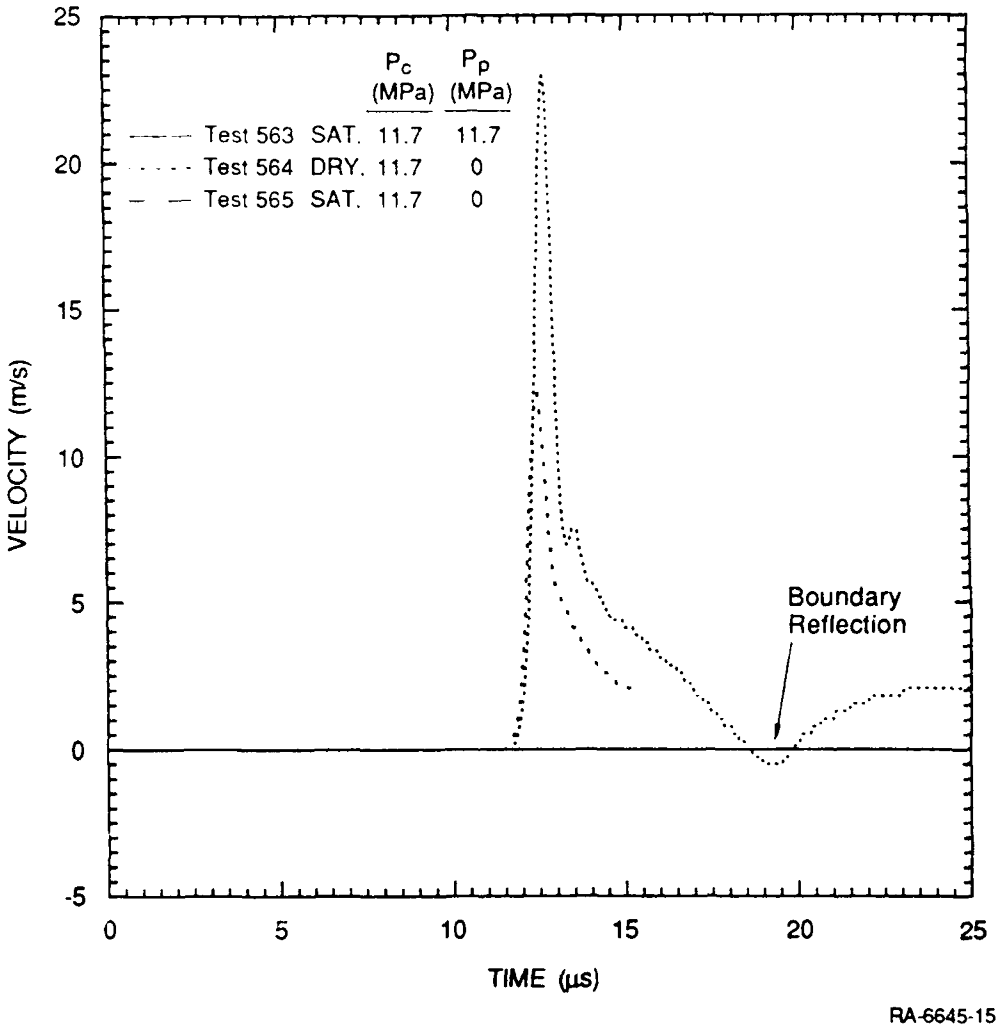

Figure 15. Particle velocity histories for three different pore conditions at 65-mm range in Sierra White granite.

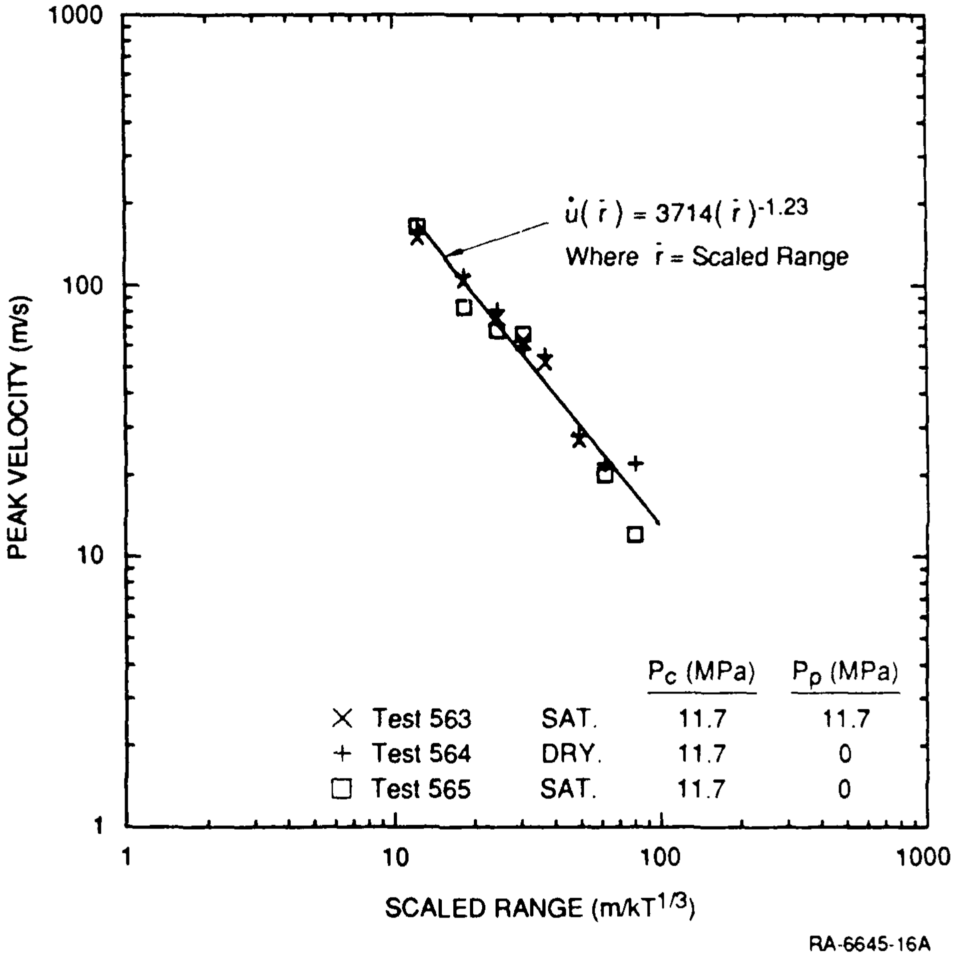

Figure 16. Attenuation of peak velocity for three different core conditions in Sierra White granite.

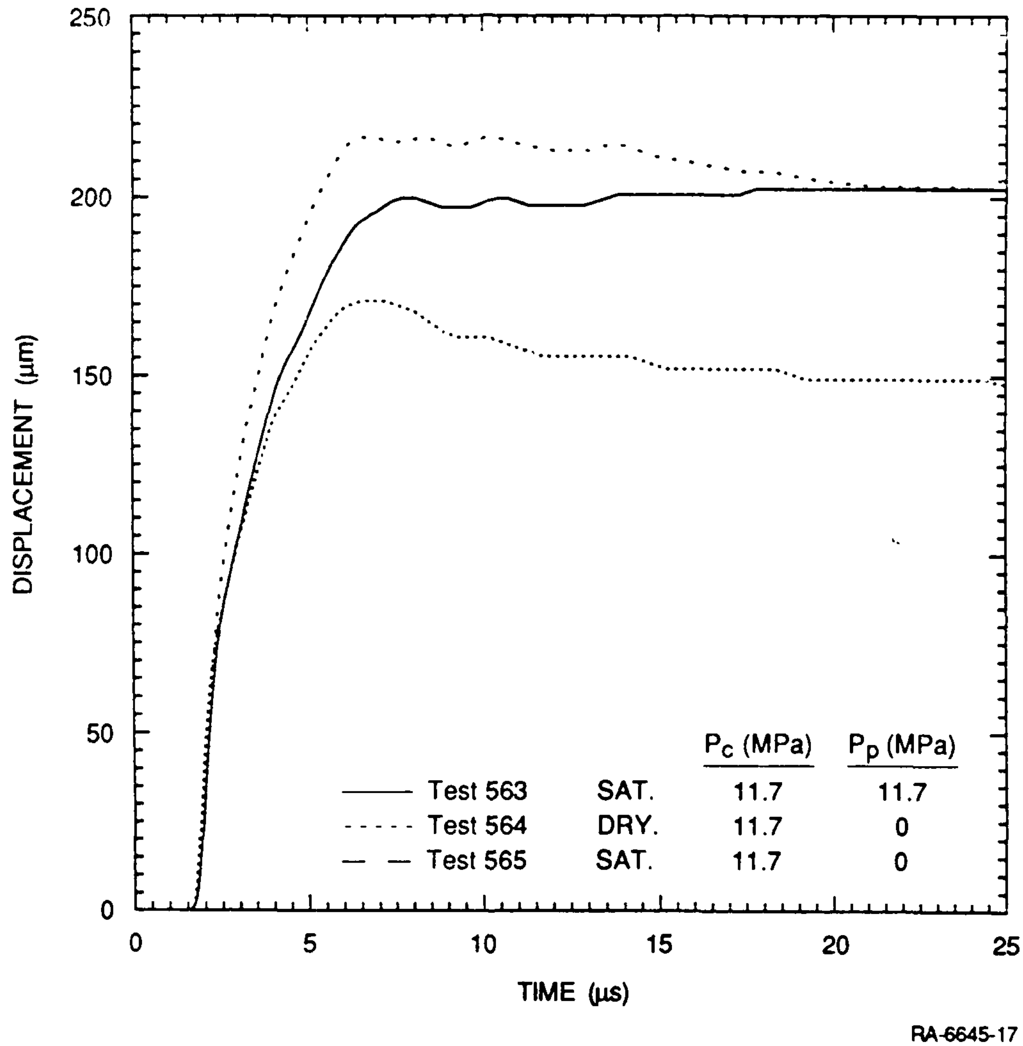

Figure 17. Displacement histories for three different pore conditions at 10-mm range in Sierra White granite.

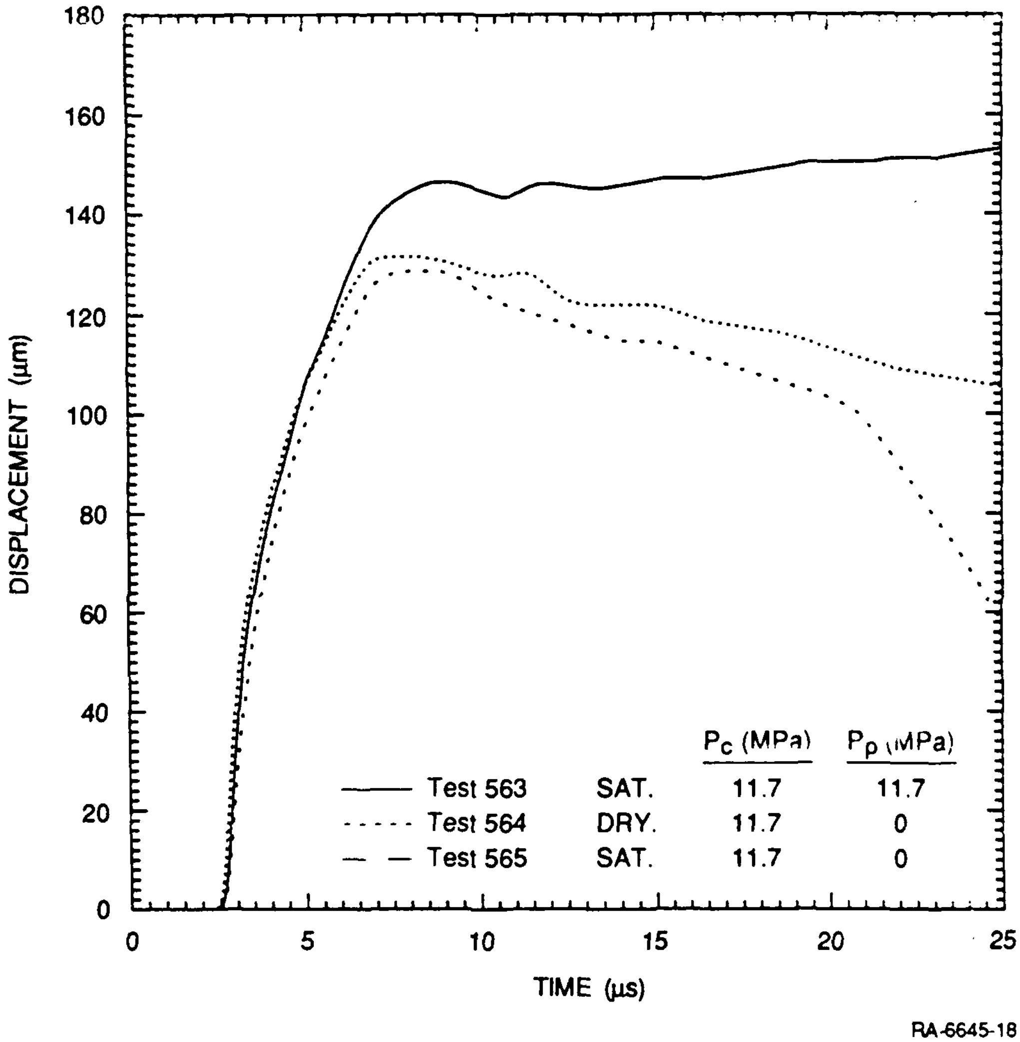

Figure 18. Displacement histories for three different pore conditions at 15-mm range in Sierra White granite.

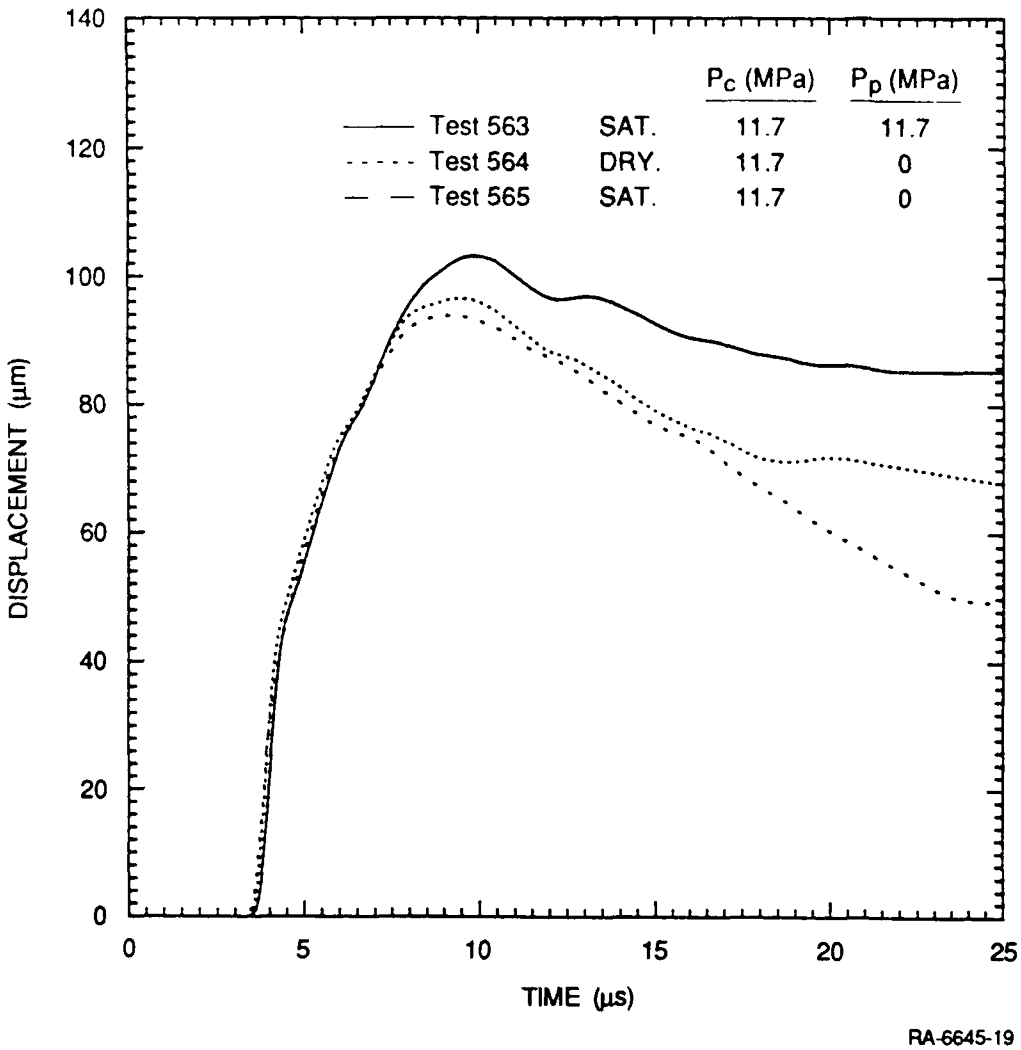

Figure 19. Displacement histories for three different pore conditions at 20-mm range in Sierra White granite.

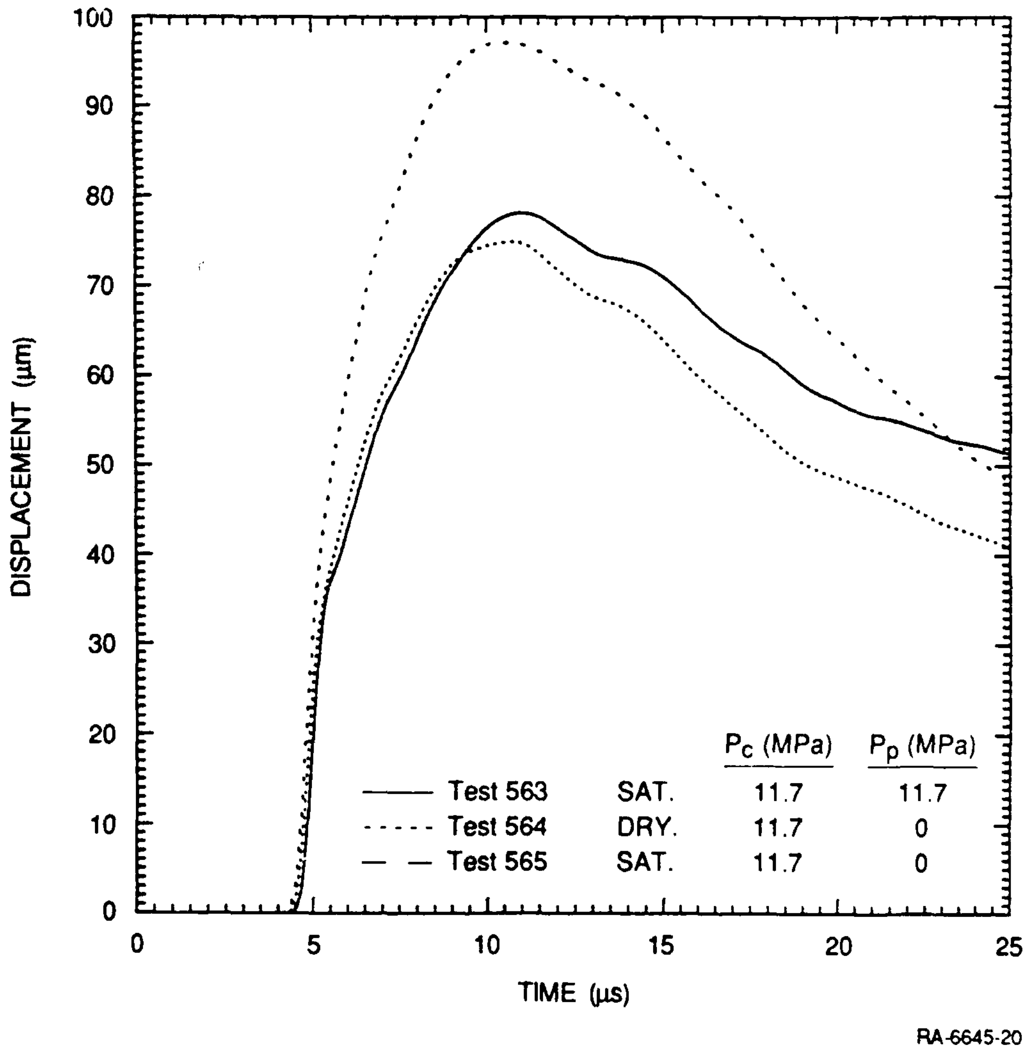

Figure 20. Displacement histories for three different pore conditions at 25-mm range in Sierra White granite.

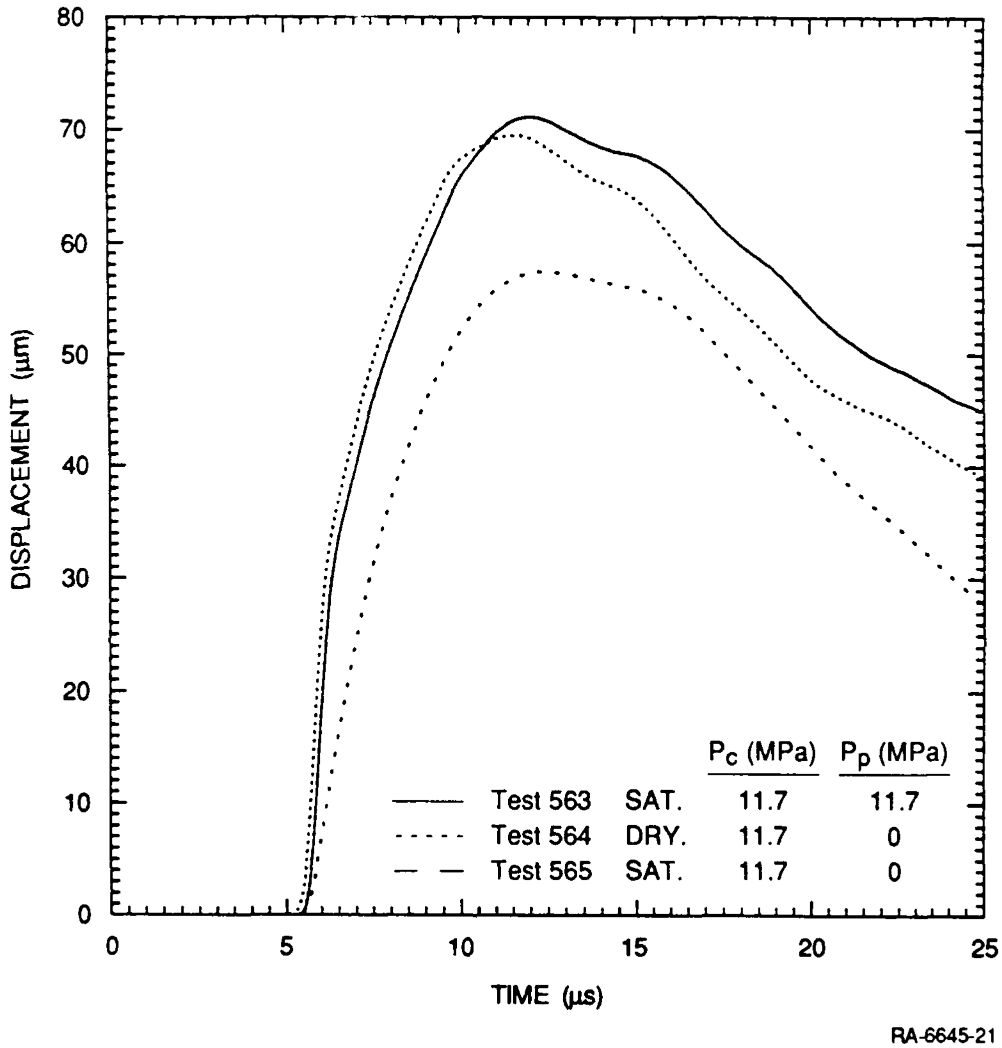

Figure 21. Displacement histories for three different pore conditions at 30-mm range in Sierra White granite.

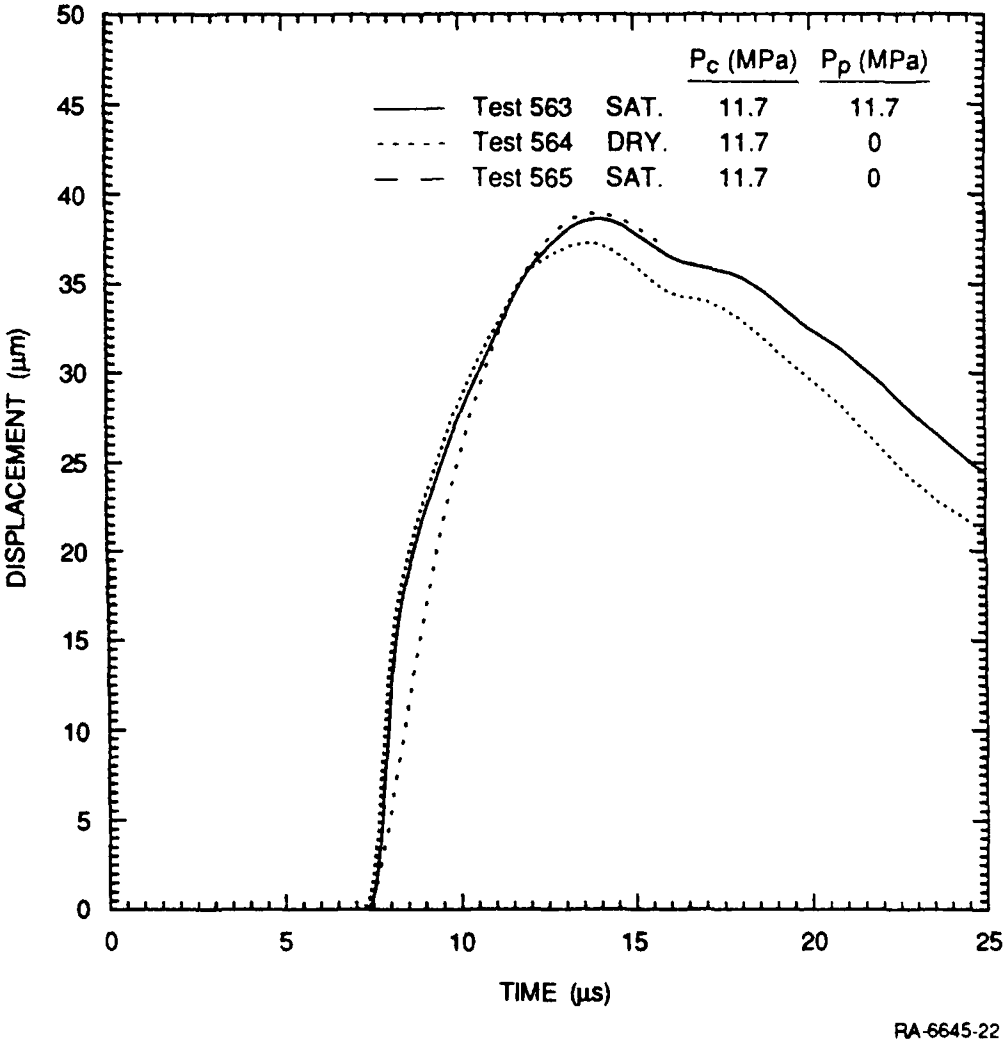

Figure 22. Displacement histories for three different pore conditions at 40-mm range in Sierra White granite.

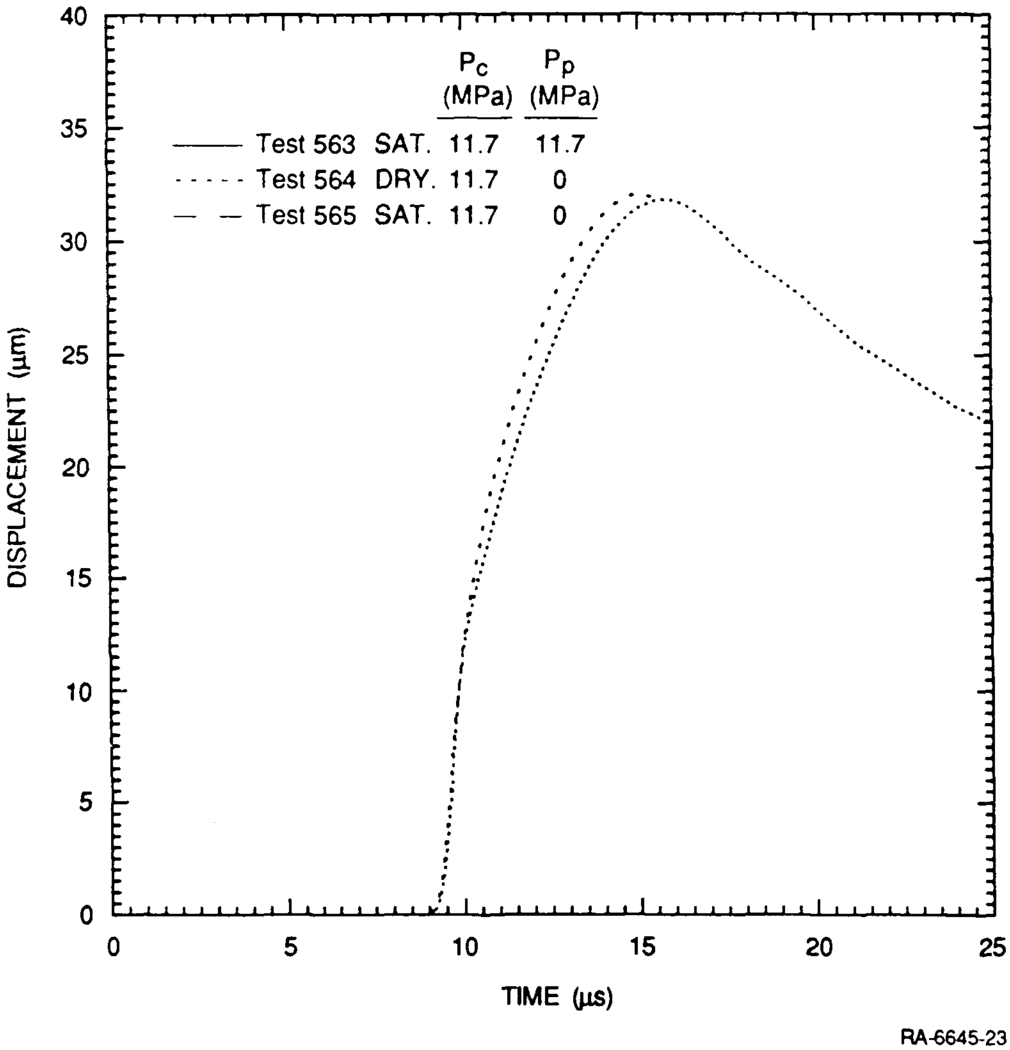

Figure 23. Displacement histories for three different pore conditions at 50-mm range in Sierra White granite.

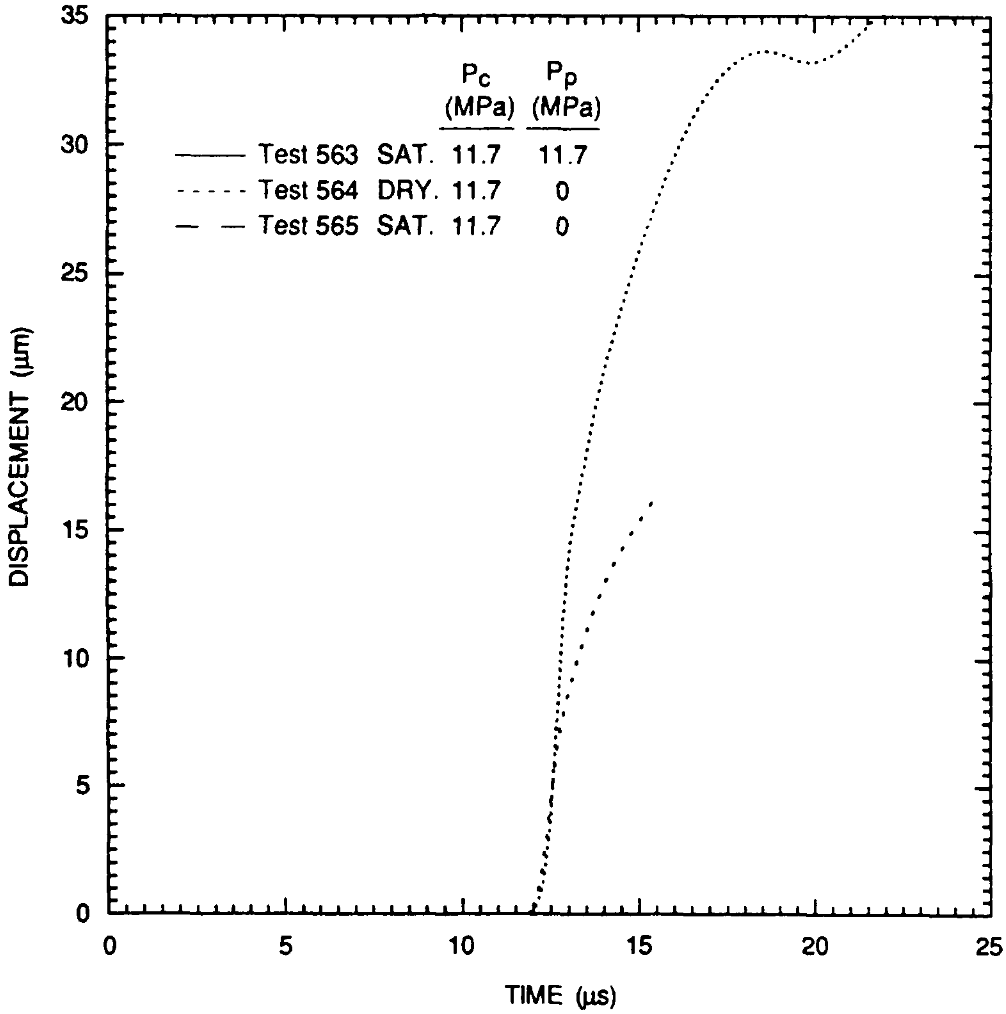

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Figure 24. Displacement histories for three different pore conditions at 65-mm range in Sierra White granite.

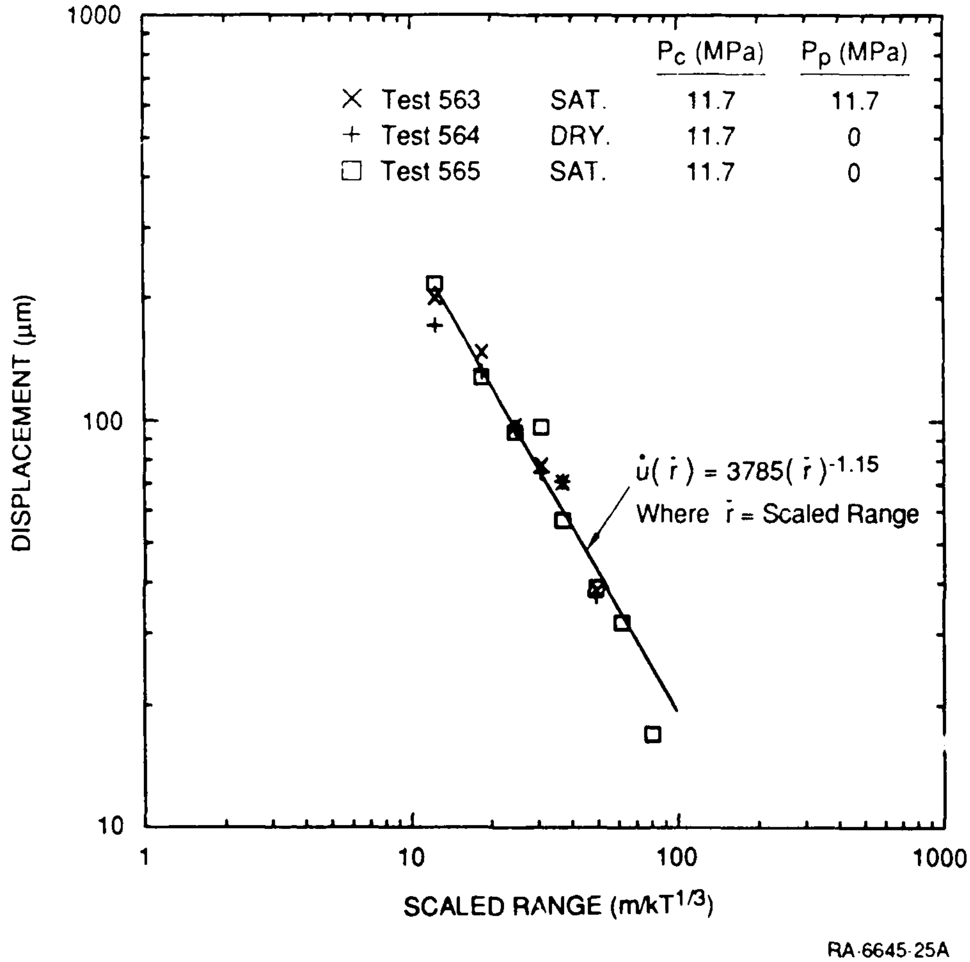

Figure 25. Attenuation of peak displacement for three different core conditions in Sierra White granite.

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